

(19)



(11)

EP 3 859 970 B1

(12)

EUROPEAN PATENT SPECIFICATION

(45) Date of publication and mention of the grant of the patent:
04.06.2025 Bulletin 2025/23

(51) International Patent Classification (IPC):
H03F 1/32 (2006.01) **H03F 1/34** (2006.01)
H03F 3/19 (2006.01) **H03F 3/21** (2006.01)

(21) Application number: **21165799.4**

(52) Cooperative Patent Classification (CPC):
H03F 1/3247; H03F 1/3223; H03F 1/3282;
H03F 1/345; H03F 3/19; H03F 3/21;
H03F 2200/105; H03F 2200/153; H03F 2200/228;
H03F 2200/393; H03F 2200/405; H03F 2200/438;
H03F 2200/451; H03F 2200/465; H03F 2200/66;

(22) Date of filing: **12.09.2012**

(Cont.)

(54) **CONTROL SYSTEM FOR A POWER AMPLIFIER**

STEUERUNGSSYSTEM FÜR EINEN LEISTUNGSVERSTÄRKER

SYSTÈME DE CONTRÔLE POUR AMPLIFICATEUR DE PUISSANCE

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO
PL PT RO RS SE SI SK SM TR

(30) Priority: **10.10.2011 EP 11275122**

(43) Date of publication of application:
04.08.2021 Bulletin 2021/31

(62) Document number(s) of the earlier application(s) in accordance with Art. 76 EPC:
12761716.5 / 2 766 988

(73) Proprietor: **Airbus Defence and Space Limited**
Stevenage, Hertfordshire SG1 2AS (GB)

(72) Inventor: **GOSS, Martin**
Portsmouth, Hampshire PO3 5PU (GB)

(74) Representative: **Cork, Robert et al**
Venner Shipley LLP
200 Aldersgate
London
EC1A 4HD (GB)

(56) References cited:
WO-A1-00/16473 WO-A1-97/28598
US-A- 3 900 823 US-A1- 2007 184 794
US-B1- 6 385 436

EP 3 859 970 B1

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

(52) Cooperative Patent Classification (CPC): (Cont.)
H03F 2200/78; H03F 2201/3227; H03F 2201/3231;
H03F 2201/3233

Description

Field of the Invention

[0001] The present invention relates to a control system for a power amplifier. In particular, the present invention relates to a control system which controls a power amplifier based on an error signal related to a phase difference between a delayed first signal derived from an input signal and a second signal derived from an amplified signal.

Background of the Invention

[0002] Power amplifiers are used in communications satellites to amplify RF signals. Such power amplifiers are known to exhibit nonlinearity, whereby the gain and phase of the amplified output RF signal varies nonlinearly with the input signal power. To compensate for this, gain and phase distortions can be applied to the input signal before it reaches the amplifier stage, so as to maintain a constant gain and phase of the output signal.

[0003] Figure 1 illustrates an open-loop control system used in a conventional communications satellite to control the gain and phase of the input signal. The system comprises a power amplifier 101, a variable attenuator 102, a phase shifter 103, an input coupler 104, a detector 105, a processor 106 and a memory 107. An initial calibration procedure is carried out in which the response of the amplifier 101 is characterised over a range of different signal powers. A lookup table (LUT) is created to record suitable gain and phase predistortions to be applied to the input signal for any given power level. The LUT is stored in the memory 107.

[0004] During operation, the detector 104 measures the power level of a coupled input signal received from the input coupler 103. The processor 106 then determines the power of the input signal RF_{IN} based on a known coupling factor of the input coupler 103. The processor 106 searches the LUT to determine how the gain and phase of the input signal should be adjusted, and controls the variable attenuator 102 and phase shifter 103 to apply the appropriate gain and phase predistortions.

[0005] However, a drawback of this approach is the lengthy calibration procedure, which can take up to 48 hrs.

[0006] US 2007/184794 A1 discloses an RF power amplifier controller circuit including a calibrated phase control loop. US 6385436 B1 discloses a distortion compensation circuit incorporated in a communications apparatus that is used for satellite communications, ground microwave communications, mobile telecommunications and the like. WO 00/16473 A1 discloses a method of adjusting the amplitude and the phase of the RF input signal to produce an adjusted RF input signal. WO 97/28598 A1 discloses a polar envelope correction mechanism for enhancing the linearity of an RF/microwave

power amplifier. US 3900823 A discloses a signal processing system which separately processes the amplitude component of the input signal and the component of frequency or phase or both frequency and phase.

Summary of the Invention

[0007] According to the present invention, there is provided an apparatus for controlling a gain and phase of an input signal input to a power amplifier, according to claim 1.

[0008] The apparatus may further comprise an input coupler configured to receive the input signal and output the third signal, the input coupler having a first coupling factor, and an output coupler configured to receive the amplified signal and output the fourth signal, the output coupler having a second coupling factor, wherein the first and second coupling factors are selected such that when the amplified signal has the predetermined gain, the third signal and the fourth signal have substantially the same power level.

[0009] The amplified signal may be clipped by the power amplifier, and the apparatus may further comprise a limiter configured to clip the input signal in correspondence with the clipping of the amplified signal by the power amplifier, such that the third signal received by the first detector and the fourth signal received by the second detector are clipped by substantially the same amount.

[0010] The phase control loop may comprise delaying means for delaying the first signal, error signal generating means for generating the error signal based on the second signal and the delayed first signal, a detector for measuring a power of the error signal and processing means configured to control the phase control means based on the measured power of the error signal, wherein the delaying means are configured such that the electrical length of a first path to the error signal generating means via the power amplifier is substantially the same as the electrical length of a second path to the error signal generating means via the delaying means.

[0011] The processing means may be configured to control the phase control means in order to minimise the measured power of the error signal.

[0012] The current gain and phase of the amplified signal may be dependent on an operational history of the power amplifier.

[0013] The power amplifier may be a Gallium Nitride GaN solid-state power amplifier.

[0014] A satellite may comprise a power amplifier and the apparatus, the apparatus being configured to control the gain and phase of the input signal input to the power amplifier.

[0015] According to the present invention, there is also provided a method for controlling a gain and phase of an input signal input to a power amplifier, according to claim 8.

Brief Description of the Drawings

[0016] Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 illustrates a conventional control system for a power amplifier;

Figure 2 illustrates a control system for a power amplifier according to an embodiment of the present invention;

Figure 3 illustrates details of gain and phase control loops for controlling a power amplifier, according to an embodiment of the present invention;

Figure 4 is a graph comparing the gain control performance of a conventional open-loop control system with the control system of Fig. 3;

Figure 5 is a graph comparing the phase control performance of a conventional open-loop control system with the control system of Fig. 3;

Figure 6 is a graph illustrating an improvement in the gain error when a limiter is used to clip the RF_{IN} signal to the same extent as the RF_{OUT} signal is clipped by the power amplifier;

Figure 7 illustrates a control system in which gain and phase control is performed using a single feed-forward control loop, according to an embodiment of the present invention;

Figure 8 is a graph comparing the gain control performance of the conventional open-loop control system with the control system of Fig. 7; and

Figure 9 is a graph comparing the phase control performance of the conventional open-loop control system with the control system of Fig. 7.

Detailed Description

[0017] Referring now to Fig. 2, a system for controlling the gain and phase of an input signal of a power amplifier is illustrated, according to an embodiment of the present invention. The system comprises a power amplifier 201, a gain control module 202, a phase control module 203, a gain control loop 210 for controlling the gain control module 202, and a phase control loop 220 for controlling the phase control module 203. The gain control module 202 may, for example, be a variable attenuator such as the one shown in Fig. 1, and the phase control module 203 may, for example, be a phase shifter such as the one shown in Fig. 1. The gain control module 202 and phase control module 203 can be controlled to change the gain and phase, respectively, of the input RF signal (RF_{IN}) before it is input to the power amplifier 201. Although in Fig. 2 the RF_{IN} signal is input to the phase control module 203 before the gain control module 202, in other embodiments the order of the phase control and gain control modules may be reversed.

[0018] The gain control and phase control loops 210, 220 each receive a signal derived from the RF_{IN} signal

and a signal derived from the output RF signal (RF_{OUT}). Each control loop 210, 220 is therefore able to monitor both the RF_{IN} and RF_{OUT} signals.

[0019] The gain control loop 210 and phase control loop 220 are configured to control the gain control module 202 and the phase control module 203 respectively, to apply gain and phase predistortions to the RF_{IN} signal in order to maintain linearity of the power amplifier 201.

[0020] Because the control loops 210, 220 are configured to monitor the output signal RF_{OUT} , the gain and phase of the input signal RF_{IN} can be adjusted based on a current value of the output signal, i.e. based on the current performance of the power amplifier. Therefore in the present embodiment, it is not necessary to make assumptions about the behaviour of the amplifier. As such, a calibration procedure is not required for the control system shown in Fig. 2.

[0021] Also, because the control system of Fig. 2 monitors the RF_{OUT} signal produced by the power amplifier 201, the control system can accurately control power amplifiers that exhibit hysteresis-type memory effects, in which the current performance of the amplifier is dependent on its operational history. That is, the current gain and phase of the amplified signal may be dependent on the operational history of the power amplifier. The operational history can include recent operating parameters of the power amplifier, such as input signal power and a gain and/or phase applied to the input signal, as well as environmental parameters to which the amplifier has recently been exposed. For example, for any given power level of the RF_{IN} signal or temperature of the amplifier, the amplifier may amplify the signal differently depending on whether the amplifier was recently used to amplify a high-power signal, or to amplify a low-power signal. One such type of power amplifier that exhibits significant memory effects is a Gallium Nitride (GaN) amplifier. Therefore embodiments of the present invention may be particularly suitable for controlling GaN amplifiers. In contrast, the conventional open-loop control system of Fig. 1 cannot be used with amplifiers that exhibit a hysteresis-type memory effect.

[0022] Furthermore, in comparison to the conventional control system of Fig. 1, the control system of Fig. 2 uses separate control loops 210, 220 to control the gain and phase of the input signal. Therefore the processing performed in each control loop can be simplified, since each loop controls only one variable, i.e. the gain or the phase. Accordingly, in Fig. 2 the control system can have a faster response time than the conventional control system of Fig. 1.

[0023] Referring now to Fig. 3, gain and phase control loops for controlling a power amplifier are schematically illustrated in detail, according to an embodiment of the present invention. Although one such structure is shown in Fig. 3, the invention is not limited to this arrangement. In general, the gain control loop and phase control loop may have any structure that provides the required functionality.

[0024] As shown in Fig. 3, the control system comprises a gain control module 302 and a phase control module 303, coupled to the input of a power amplifier 301. The system further comprises a first input coupler 304 and second input coupler 305. The first input coupler 304 is configured to direct a first coupled input signal, which is a coupled portion of the RF_{IN} signal, to the gain control loop 310. The second input coupler 305 is configured to direct a second coupled input signal, which is a coupled portion of the RF_{IN} signal, to the phase control loop 320. The system further comprises a first output coupler 306 and a second output coupler 307. The first output coupler 306 is configured to direct a first coupled output signal, which is a coupled portion of the RF_{OUT} signal, to the gain control loop 310. The second output coupler 307 is configured to direct a second coupled output signal, which is a coupled portion of the RF_{OUT} signal, to the phase control loop 320.

[0025] The first and second input couplers 304, 305 may be formed as a single unit or as separate units, and the first and second output couplers 306, 307 may be formed as a single unit or as separate units. The first and second input couplers 304, 305 may be configured to have the same coupling factor such that the first and second coupled input signals have the same power level. Alternatively, the first and second input couplers 304, 305 may be configured to have different coupling factors such that the first and second coupled input signals have different power levels. Similarly, the first and second output couplers 306, 307 may be configured to have the same coupling factor such that the first and second coupled output signals have the same power level, or may be configured to have different coupling factors such that the first and second coupled output signals have different power levels. The coupling factor of each of the first and second input couplers 304, 305 and first and second output couplers 306, 307 may be chosen to ensure that during normal operation of the power amplifier 301 and control system, the first and second coupled input and output signals have power levels that can be detected by the gain and phase control loops 310, 320.

[0026] Although in Fig. 3 separate couplers 304, 305 are used to generate the first coupled input signal and second coupled input signal, in other embodiments a single input coupler may be provided. In such embodiments, means for splitting the coupled input signal into the first and second coupled input signals may be provided. For example, a rat-race coupler could be used to split a coupled input signal into the first coupled input signal to be sent to the gain control loop, and the second coupled input signal to be sent to the phase control loop. Similarly, a single output coupler connected to splitting means such as a rat-race coupler could be used to generate both the first and second output signals.

[0027] In the present embodiment, the gain control loop 310 comprises an input detector 311 arranged to receive the first coupled input signal from the first input coupler 304. The input detector 311 is configured to

measure the power level of the first coupled input signal, and send a signal representing the measured power to a first differential amplifier 313. For example, the input detector 311 may be a root-mean-squared (RMS) detector configured to output a voltage that is representative of the RMS power of the first coupled input signal.

[0028] The gain control loop 310 further comprises an output detector 312 arranged to receive the first coupled output signal from the first output coupler 306. The output detector 312 is configured to measure the power level of the first coupled output signal, and send a signal representing the measured power to a second differential amplifier 314. Like the input detector 311, the output detector 312 may be an RMS detector configured to output a voltage that is representative of the RMS power of the first coupled output signal.

[0029] In more detail, the input detector 311 includes two matched RMS detectors biased by the same DC bias. One of the detectors receives the RF first coupled input signal, and outputs the measured power level to one input of the first differential amplifier 313. The other detector does not receive the first coupled input signal, and outputs a reference signal to the other input of the first differential amplifier 313. The first differential amplifier 313 therefore outputs an amplified signal that is representative of the power level of the first coupled input signal. The output detector 312 and second differential amplifier 314 are arranged similarly to the input detector 311 and first differential amplifier 313. However, in other embodiments other arrangements may be used to detect power levels of the first coupled input signal and first coupled output signal.

[0030] In the present embodiment, the gain control loop 310 further comprises a scaling amplifier 315 coupled to an output of the first differential amplifier 314. The scaling amplifier is configured to amplify the signal from the first differential amplifier 314, to account for any mismatch between the input detector 311 and the output detector 312. That is, if the input detector 311 and output detector 312 are not matched, each detector may output a different voltage for any given signal power level.

[0031] Although in the present embodiment an amplifier is provided as a means for scaling the signal produced by one of the detectors, in other embodiments alternative scaling means may be used. Instead of amplifying the signal from one of the detectors, the scaling means could be arranged to pull down the output of one of the differential amplifiers 313, 314 by a suitable amount, for example using a resistive divider, to compensate for any mismatch between the detectors. Also, although in Fig. 3 the scaling means, i.e. the scaling amplifier 315, is coupled to an output of the first differential amplifier 313, the present invention is not limited to this particular arrangement. For example, the scaling means 315 could be coupled to the output of the second differential amplifier 314.

[0032] Continuing with reference to Fig. 3, the scaled output of the first differential amplifier 313 and the output

of the second differential amplifier 314 are coupled to the inputs of another differential amplifier 316, hereinafter referred to as the loop amplifier 316. The loop amplifier 316 generates a gain control signal which is representative of a difference between the scaled output of the first differential amplifier 313 and the output of the second differential amplifier 314. The gain control signal is sent to the gain control module 302, which determines based on the value of the gain control signal whether to adjust the gain being applied to the RF_{IN} signal. For example, the gain control module 302 may be configured to adjust the gain in order to minimise the value of the gain control signal received from the loop amplifier 316.

[0033] In summary, the gain control loop 310 is configured to control the gain control module 302 based on a difference in power between the first coupled input signal and the first coupled output signal. Although one structure of the gain control loop 310 is shown in Fig. 3, in other embodiments other arrangements may be used.

[0034] As shown in Fig. 3, the phase control module 303 is controlled by a separate phase control loop 320. As described above, the phase control loop 320 receives the second coupled input signal from the second input coupler 305, and receives the second coupled output signal from the second output coupler 307. The second coupled input signal and second coupled output signal are combined in a coupler 322. However, before being input to the coupler 322, the second coupled input signal is passed through a delay line 321. The delay line 321 is configured to delay the second coupled input signal to ensure the same electrical length across both signal paths for frequencies in the RF_{IN} signal. That is, the delay line 321 is configured so that the electrical length of the "through path" including the gain and phase control modules 302, 303, the power amplifier 301, the second output coupler 307 and the coupler 322, is the same as the electrical length of the "coupled-through path" including the delay line 321 and the coupler 322.

[0035] In this way, the second coupled input signal and the second coupled output signal arriving at the coupler 322 at any point in time are controlled to correspond to the same part of the original RF_{IN} signal. That is, the delay line 321 in the phase control loop 320 is arranged to delay the first signal before the error signal is obtained by the coupler 322, such that the delayed first signal and the second signal used to obtain the error signal correspond to the same part of the input signal RF_{IN} . Therefore the phase control loop 320 may be referred to as a feed-forward loop, since the second coupled input signal is "fed forward" and compared against the corresponding portion of the output RF_{OUT} signal.

[0036] A signal path from the second input coupler 305 to the coupler 322 via the delay line 321 may be referred to as a "feed-forward path". As described above, the signal path through the phase control module 303, gain control module 302, and power amplifier 301 to the second output coupler 307 may be referred to as the "through path", and a signal path from the second output

coupler 307 to the coupler 322 may be referred to as the "coupled-through path". The delay line 321 is therefore configured such that the electrical length of the feed-forward path is substantially the same as the combined electrical lengths of the through path and the coupled-through path. In the present embodiment, the delay line 321 is physically embodied as a length of coaxial cable having an appropriate physical length to achieve the required delay. However, other arrangements may be used in other embodiments.

[0037] In the present embodiment, the phase control loop 320 is configured such that when the amplified RF_{OUT} signal output by the power amplifier 301 has the correct phase, the second coupled input signal and second coupled output signal arrive at the coupler 322 in-phase. The coupling factors of the second input coupler 305 and second output coupler 307 may be chosen such that when the power amplifier 301 is operating at the desired gain, the second coupled input signal and second coupled output signal have the same power level. Alternatively, an attenuator may be used to pull down the second coupled input signal or the second coupled output signal to the correct power level.

[0038] The coupler 322 is a 180° coupler, and therefore when the second coupled input signal and second coupled output signal are combined in the coupler 322, they will cancel at an output of the coupler 322 if amplified RF_{OUT} signal outputted from the power amplifier 301 has the correct phase. In effect, the phase control loop 320 is arranged to subtract the second coupled input signal from the second coupled output signal to obtain a difference between the two signals, as an error signal. However, if the RF_{OUT} signal does not have the correct phase, the second coupled output signal will not be in-phase with the second coupled input signal as they arrive at the coupler 322. In this case, the signals will not completely cancel, and the amplitude of the error signal output by the coupler 322 is representative of the phase difference between the signals. The phase control loop 320 can therefore detect whether the phase of the RF_{OUT} signal is offset from the desired value, for example as a result of nonlinear phase distortions introduced by the power amplifier 301.

[0039] The error signal output by the coupler 322 is sent to a detector 323, which may be an RMS detector similar to the input detector 311 and output detector 312 of the gain control loop 310. The detector 323 measures the power level of the error signal, and outputs a signal representing the measured power to a processor 324. The processor is configured to adjust a phase adjustment applied to the RF_{IN} signal by the phase control module 303, so as to minimise the error signal power level measured by the detector 323.

[0040] Although in the present embodiment, an error signal is obtained by taking the difference between the coupled input and output signals, in other embodiments the phase control loop 320 may be configured to add the coupled signals together to produce the error signal. For

example, the second coupled input signal and second coupled output signal could be arranged to be in-phase when they arrive at the coupler 322, such that the signals add together instead of cancelling. In this case, the processor can be arranged to vary the phase applied to the RF_{IN} signal so as to maximise the measured power of the error signal.

[0041] As described above, using separate control loops to control the gain and phase applied to the RF_{IN} signal offers the advantage that the processing algorithm can be simplified in comparison to a conventional control system, since each control loop only deals with a single variable. Therefore a control system such as the one shown in Fig. 3 can operate with a shorter response time compared to a conventional control system. Furthermore, the gain and phase control can be accurately applied even when the gain control behaves as a phase shifter, which typically occurs when the power amplifier is operated at, or close to, saturation. In this case, varying the gain can affect the phase of the RF_{OUT} signal, but the separate phase control loop can detect this change and automatically adjust the phase to compensate.

[0042] Although in the embodiment of Fig. 3, the gain control loop is implemented using analogue components, in other embodiments the gain control loop may be digitised. For example, a field programmable gate array (FPGA) or application specific integrated circuit (ASIC) may be configured to provide similar functionality to the analogue gain control loop of Fig. 3, in order to control the gain control module. Additionally, although in the present embodiment the gain and phase control loops are used to control an RF power amplifier, other embodiments may be used at different frequencies, i.e. not only at RF.

[0043] In the embodiment shown in Fig. 3, the phase control loop is a feedforward loop similar to a signal cancellation circuit of a feedforward linearization circuit. The phase control loop of Fig. 3 differs from a feedforward linearization circuit in that the error signal obtained by the coupler 322 is not subsequently combined with the RF_{OUT} output signal of the power amplifier to cancel intermodulation products, as would normally happen in the error cancellation circuit of a feedforward linearization circuit. Instead, a power of the error signal is detected and used to determine a phase to be applied to the RF_{IN} input signal.

[0044] Referring now to Fig. 4, a graph comparing the gain control performance of a conventional open-loop control system with the control system of Fig. 3 is illustrated. The graph shows the variation in gain error (Delta Gain) over a range of output signal RF_{OUT} power levels. The gain error is the difference between the actual gain and the target gain. A first curve 401, shown as a solid line in Fig. 4, illustrates the gain error for a range of output power levels when the control system of Fig. 3 is used to control a GaN power amplifier. A second curve 402, shown as a dashed line in Fig. 4, illustrates the gain error over the same power range when a conventional open-

loop control system, such as the one shown in Fig. 1, is used to control the same GaN power amplifier. As shown in Fig. 4, the control system of Fig. 3 achieves substantially more stable gain control than is possible with the conventional open-loop control system.

[0045] Referring now to Fig. 5, a graph comparing the phase control performance of a conventional open-loop control system with the control system of Fig. 3 is illustrated. The graph shows the variation in phase error (Delta Phase) over the same power range used in Fig. 4. A first curve 501, shown as a solid line in Fig. 5, illustrates the phase error when the control system of Fig. 3 is used to control the GaN power amplifier. A second curve 502, shown as a dashed line in Fig. 5, illustrates the phase error when a conventional open-loop control system is used to control the GaN power amplifier. As shown in Fig. 5, the control system of Fig. 3 achieves substantially more stable phase control than is possible with the conventional open-loop control system.

[0046] Preferably, the input and output detectors of the gain control loop should be RMS detectors. However, if the detectors are not good RMS detectors, a limiter can be used to clip the input signal RF_{IN} before the signal reaches the first input coupler. In more detail, when the RF_{IN} signal has a high peak-to-average ratio (PAR), the amplified signal RF_{OUT} produced by the power amplifier can become clipped when the amplifier is driven to a high gain level. In this event the RF_{OUT} signal will have a lower PAR than the RF_{IN} signal, and accordingly the first coupled output signal will have a lower PAR than the first coupled input signal. If the input and output detectors are not good RMS detectors, the detectors may give a different measured power for signals having a different PAR, even when the RMS power of the signals is the same. Therefore when the RF_{OUT} signal is clipped relative to the RF_{IN} signal and the detectors are not good RMS detectors, different power levels may be measured by the input and output detectors even when the signals have the same RMS power level. This can result in the gain control being incorrectly applied.

[0047] To compensate for this, embodiments of the present invention in which the detectors are not good RMS detectors may further include a limiter coupled to an input of the first input coupler. The limiter is configured to clip the RF_{IN} signal to the same extent as the RF_{OUT} signal is clipped by the power amplifier. Accordingly, the first coupled input signal and first coupled output signal are clipped to the same extent, and the gain control error can be avoided.

[0048] Figure 6 is a graph illustrating the gain error over a range of output power levels, when the input and output detectors of the gain control loop are not good RMS detectors. A first curve 601, shown as a solid line in Fig. 6, illustrates the gain error when a limiter is used to clip the RF_{IN} signal. For comparison purposes, a second curve 602 is also provided, shown as a dashed line in Fig. 6, to illustrate the gain error when the RF_{IN} signal is not clipped. As shown in Fig. 6, without the limiter

the gain error varies by as much as ± 1.1 dB, but by using the limiter this can be improved to ± 0.83 dB. By way of comparison, if good RMS detectors are used as in the embodiment of Fig. 3, the gain error varies by ± 0.13 dB, as shown in Fig. 4.

[0049] A further embodiment of the present invention will now be described with reference to Fig. 7. The control system shown in Fig. 7 may be included in a satellite, such as a communications satellite, to control a power amplifier of the satellite. In this embodiment, gain and phase control is performed using a single feed-forward control loop 720. Like the embodiment of Fig. 3, the present embodiment comprises a power amplifier 701, gain control and phase control modules 702, 703 coupled to an input of the power amplifier 701, and input and output couplers 705, 707 configured to direct coupled input and coupled output signals, respectively, to the feed-forward control loop 720. Also like the embodiment of Fig. 3, the feed-forward control loop 720 includes a coupler 722 for combining the coupled input signal and coupled output signal, and a delay line 721 for delaying the coupled input signal before it is input to the detector 722. The coupler 722 outputs an error signal to a detector 723, which measures the power level of the error signal and sends a signal representing the measured power to a processor 724. As with the phase control loop 320 of Fig. 3, the control loop 720 of Fig. 7 is arranged to delay the first signal before obtaining the error signal, such that the delayed first signal and the second signal used to obtain the error signal correspond to the same part of the input signal RF_{IN} .

[0050] A detailed description of the operation of the feed-forward control loop 720 will be omitted to maintain brevity, since the error signal is obtained in a similar manner as in the embodiment of Fig. 3. However, in the present embodiment, the processor 724 determines, based on the measured power of the error signal, whether to adjust the gain and phase applied to the RF_{IN} signal before it is input to the power amplifier 701. As such, the processor 724 is coupled to both the gain control module 702 and the phase control module 703 to control the gain and phase of the RF_{IN} signal. Therefore, in the present embodiment, gain and phase control is performed using a single control loop.

[0051] Referring now to Fig. 8, a graph comparing the gain control performance of the conventional open-loop control system with the control system of Fig. 7 is illustrated. The graph shows the variation in gain error over a range of RF_{OUT} power levels. A first curve 801, shown as a solid line in Fig. 8, illustrates the gain error for a range of RF_{OUT} power levels when the control system of Fig. 7 is used to control a GaN power amplifier. A second curve 802, shown as a dashed line in Fig. 8, illustrates the gain error over the same power range when a conventional open-loop control system, such as the one shown in Fig. 1, is used to control the same GaN power amplifier. As shown in Fig. 8, the control system of Fig. 7 achieves substantially more stable gain control than is possible

with the conventional open-loop control system.

[0052] Referring now to Fig. 9, a graph comparing the phase control performance of the conventional open-loop control system with the control system of Fig. 7 is illustrated. The graph shows the variation in phase error over a range of RF_{OUT} power levels. A first curve 901, shown as a solid line in Fig. 9, illustrates the phase error for a range of signal powers when the control system of Fig. 7 is used to control the GaN power amplifier. A second curve 902, shown as a dashed line in Fig. 9, illustrates the phase error over the same power range when the conventional open-loop control system is used to control the same GaN power amplifier. As shown in Fig. 9, the control system of Fig. 7 achieves substantially more stable phase control than is possible with the conventional open-loop control system.

[0053] In comparison with the embodiment of Fig. 3, the control system of Fig. 7 offers less stable gain control over a given range of output signal power, because a single control loop is used to control both the gain and phase. A more complex processing algorithm is required when a single loop controls both gain and phase, and accordingly the response time of the feed-forward control loop 720 of Fig. 7 is slower in comparison to the gain control and phase control loops 310, 320 of Fig. 3. Nonetheless, the embodiment of Fig. 7 still offers a substantial improvement over the conventional open-loop control system.

[0054] In more detail, when a conventional open-loop control system is used to control the gain and phase, the gain error can only be controlled to within a range of ± 2 dB, as shown in Figs. 4 and 8. When a single feed-forward control loop is used to control both gain and phase, as in the embodiment of Fig. 7, this is improved to ± 0.23 dB, as shown in Fig. 8. When a separate closed loop is used to control the gain, as in the embodiment of Fig. 3, this is improved yet further to ± 0.13 dB, as shown in Fig. 4.

[0055] Similarly, when the conventional open-loop control system is used to control both gain and phase, the phase error can only be controlled to within a range of $\pm 20^\circ$, as shown in Figs. 5 and 9. When a single feed-forward control loop is used to control both gain and phase, as in the embodiment of Fig. 7, this is improved to $\pm 2.2^\circ$, as shown in Fig. 9. When a separate feed-forward control loop is used to control the phase, as in the embodiment of Fig. 3, this is improved yet further to $\pm 1.8^\circ$, as shown in Fig. 5.

[0056] The results shown in Figs. 4, 5, 8 and 9 were obtained during preliminary testing of embodiments constructed using relatively low-quality components. Nevertheless, as described above these early embodiments still offer a measurable improvement over the standard open-loop control system of Fig. 1, and a greater improvement will be expected following further optimisation.

[0057] Although embodiments of the present invention have been described in relation to controlling GaN power amplifiers that exhibit hysteresis-like memory effects,

other embodiments may be used to control power amplifiers that do not exhibit such memory effects, for example GaAs-based devices. In these cases, a control system according to the present invention may still offer an advantage over the conventional open-loop control system of Fig. 1, by virtue of an improved response time that allows the gain and phase distortions to be more quickly adjusted in response to changes in the input signal power.

[0058] Additionally, embodiments of the present invention have been described in which the gain control loop monitors both the input and output signals. However, some embodiments may be configured for use in applications where the input signal has a known constant power, and in such embodiments the gain control loop can determine a current gain of the amplified signal without monitoring the input signal, since the power level of the input signal is already known.

[0059] Furthermore, embodiments of the present invention have been described in which the power levels of signals derived from the input and output signals are measured. This can allow the use of low-power detectors even when the input and/or amplified signals are high-power signals. Alternatively, in some embodiments the power levels of the input and/or amplified signals may be directly detected, in which case the first and/or second couplers and first and/or second detectors of Fig. 3 can be omitted accordingly.

[0060] Whilst certain embodiments of the present invention have been described above, the skilled person will understand that many variations and modifications are possible without departing from the scope of the invention as defined by the accompanying claims.

Claims

1. Apparatus for controlling a gain and phase of an input signal input to a power amplifier (301), the apparatus comprising:

gain control means (302) for controlling the gain of the input signal;
 phase control means (303) for controlling the phase of the input signal;
 a gain control loop (310) configured to control the gain control means based on a power level of the input signal and a power level of an amplified signal output by the power amplifier, to obtain a predetermined gain of the amplified signal; and
 a phase control loop (320) configured to obtain an error signal related to a phase difference between a first signal derived from the input signal and a second signal derived from the amplified signal, and control the phase control means based on the error signal to obtain a predetermined phase of the amplified signal, wherein the phase control loop is arranged to

delay the first signal before obtaining the error signal, such that the delayed first signal and the second signal used to obtain the error signal correspond to the same part of the input signal, wherein the gain control loop is configured to receive a third signal derived from the input signal and a fourth signal derived from the amplified signal, wherein the gain control loop is configured to compare a power level of the third signal and a power level of the fourth signal and control the gain control means based on the result of the comparison, and wherein the gain control loop comprises:

a first detector (311) configured to measure a power level of the third signal;
 a second detector (312) configured to measure a power level of the fourth signal;

characterised in that the gain control loop comprises means (315) for scaling an output of the first detector or an output of the second detector, so that the outputs of the first and second detectors are substantially identical when the third and fourth signals have the same power.

2. The apparatus of claim 1, further comprising:

an input coupler (304) configured to receive the input signal and output the third signal, the input coupler having a first coupling factor; and
 an output coupler (305) configured to receive the amplified signal and output the fourth signal, the output coupler having a second coupling factor, wherein the first and second coupling factors are selected such that when the amplified signal has the predetermined gain, the third signal and the fourth signal have substantially the same power level.

3. The apparatus of claim 1 or 2, wherein the amplified signal is clipped by the power amplifier, the apparatus further comprising:

a limiter configured to clip the input signal in correspondence with the clipping of the amplified signal by the power amplifier, such that the third signal received by the first detector and the fourth signal received by the second detector are clipped by substantially the same amount.

4. The apparatus of any one of the preceding claims, wherein the phase control loop comprises:

delaying means (321) for delaying the first signal;
 error signal generating means (322) for gener-

- ating the error signal based on the second signal and the delayed first signal;
 a detector (323) for measuring a power of the error signal; and
 processing means (324) configured to control the phase control means based on the measured power of the error signal,
 wherein the delaying means is configured such that the electrical length of a first path to the error signal generating means via the power amplifier is substantially the same as the electrical length of a second path to the error signal generating means via the delaying means.
- 5
- 10
5. The apparatus of claim 4, wherein the processing means is configured to control the phase control means in order to minimise the measured power of the error signal.
- 15
6. The apparatus of any one of the preceding claims, wherein a current gain and phase of the amplified signal is dependent on an operational history of the power amplifier.
- 20
7. A satellite comprising:
- 25
- a power amplifier; and
 the apparatus of any one of the preceding claims, configured to control the gain and phase of the input signal input to the power amplifier.
- 30
8. A method for controlling a gain and phase of an input signal input to a power amplifier (301), the method comprising:
- 35
- controlling the gain of the input signal based on a power level of the input signal and a power level of an amplified signal output by the power amplifier, to obtain a predetermined gain of the amplified signal;
 delaying a first signal derived from the input signal;
 obtaining an error signal related to a phase difference between the delayed first signal and a second signal derived from the amplified signal; and
 controlling the phase of the input signal according to the error signal to obtain a predetermined phase of the amplified signal,
 wherein the first signal is delayed such that the delayed first signal and the second signal used to obtain the error signal correspond to the same part of the input signal,
 wherein controlling the gain of the input signal comprises:
- 40
- 45
- 50
- 55
- using a first detector (311) to measure a power level of the third signal derived from

the input signal, and using a second detector (312) to measure a power level of a fourth signal derived from the amplified signal;
 comparing the power level of the third signal and the power level of the fourth signal; and
 controlling the gain of the input signal based on the result of the comparison,
characterised in that controlling the gain of the input signal further comprises:
 scaling an output of the first detector or an output of the second detector, so that the outputs of the first and second detectors are substantially identical when the third and fourth signals have the same power.

Patentansprüche

1. Vorrichtung zum Steuern einer Verstärkung und Phase eines Eingangssignals, das in einen Leistungsverstärker (301) eingegeben wird, wobei die Vorrichtung Folgendes umfasst:
- Verstärkungssteuerungsmittel (302) zum Steuern der Verstärkung des Eingangssignals;
 Phasensteuerungsmittel (303) zum Steuern der Phase des Eingangssignals;
 eine Verstärkungssteuerungsschleife (310), die so konfiguriert ist, dass sie die Verstärkungssteuerungsmittel basierend auf einem Leistungsniveau des Eingangssignals und einem Leistungsniveau eines verstärkten Signals, das von dem Leistungsverstärker ausgegeben wird, steuert, um eine vorbestimmte Verstärkung des verstärkten Signals zu erlangen; und
 eine Phasensteuerungsschleife (320), die so konfiguriert ist, dass sie ein Fehlersignal erlangt, das mit einer Phasendifferenz zwischen einem ersten Signal, das von dem Eingangssignal abgeleitet wird, und einem zweiten Signal, das von dem verstärkten Signal abgeleitet wird, in Beziehung steht, und die Phasensteuerungsmittel basierend auf dem Fehlersignal steuert, um eine vorbestimmte Phase des verstärkten Signals zu erlangen,
 wobei die Phasensteuerungsschleife so angeordnet ist, dass sie das erste Signal derart verzögert, bevor das Fehlersignal erlangt wird, dass das verzögerte erste Signal und das zweite Signal, die verwendet werden, um das Fehlersignal zu erlangen, demselben Teil des Eingangssignals entsprechen,
 wobei die Verstärkungssteuerungsschleife so konfiguriert ist, dass sie ein drittes Signal, das von dem Eingangssignal abgeleitet ist, und ein viertes Signal, das von dem verstärkten Signal abgeleitet ist, empfängt,

wobei die Verstärkungssteuerungsschleife so konfiguriert ist, dass sie ein Leistungsniveau des dritten Signals und ein Leistungsniveau des vierten Signals vergleicht und die Verstärkungssteuerungsmittel basierend auf dem Ergebnis des Vergleichs steuert, und wobei der Verstärkungssteuerungsschleife Folgendes umfasst:

einen ersten Detektor (311), der so konfiguriert ist, dass er ein Leistungsniveau des dritten Signals misst;

einen zweiten Detektor (312), der so konfiguriert ist, dass er ein Leistungsniveau des vierten Signals misst;

dadurch gekennzeichnet, dass die Verstärkungssteuerungsschleife Mittel (315) zum Skalieren einer Ausgabe des ersten Detektors oder einer Ausgabe des zweiten Detektors umfasst, sodass die Ausgaben des ersten und zweiten Detektors im Wesentlichen identisch sind, wenn das dritte und vierte Signal die gleiche Leistung haben.

2. Vorrichtung nach Anspruch 1, ferner umfassend:

einen Eingabekoppler (304), der so konfiguriert ist, dass er das Eingabesignal empfängt und das dritte Signal ausgibt, wobei der Eingabekoppler einen ersten Kopplungsfaktor hat; und einen Ausgabekoppler (305), der so konfiguriert ist, dass er das verstärkte Signal empfängt und das vierte Signal ausgibt, wobei der Ausgabekoppler einen zweiten Kopplungsfaktor hat, wobei der erste und zweite Kopplungsfaktor derart ausgewählt sind, dass, wenn das verstärkte Signal die vorbestimmte Verstärkung hat, das dritte Signal und das vierte Signal im Wesentlichen das gleiche Leistungsniveau haben.

3. Vorrichtung nach Anspruch 1 oder 2, wobei das verstärkte Signal durch den Leistungsverstärker übersteuert ist, wobei die Vorrichtung ferner Folgendes umfasst:

einen Begrenzer, der so konfiguriert ist, dass er das Eingabesignal entsprechend dem Übersteuern des verstärkten Signals durch den Leistungsverstärker derart übersteuert, dass das dritte Signal, das von dem ersten Detektor empfangen wird, und das vierte Signal, das von dem zweiten Detektor empfangen wird, um im Wesentlichen den gleichen Betrag übersteuert sind.

4. Vorrichtung nach einem der vorhergehenden Ansprüche, wobei die Phasensteuerungsschleife Folgendes umfasst:

Verzögerungsmittel (321) zum Verzögern des ersten Signals;

Fehlersignalgenerierungsmittel (322) zur Generieren des Fehlersignals basierend auf dem zweiten Signal und dem verzögerten ersten Signal;

einen Detektor (323) zum Messen einer Leistung des Fehlersignals; und

Verarbeitungsmittel (324), die so konfiguriert sind, dass sie die Phasensteuerungsmittel basierend auf der gemessenen Leistung des Fehlersignals steuern,

wobei die Verzögerungsmittel derart konfiguriert sind, dass die elektrische Länge eines ersten Verlaufs zu den Fehlersignalgenerierungsmitteln über den Leistungsverstärker im Wesentlichen gleich der elektrischen Länge eines zweiten Verlaufs zu den Fehlersignalgenerierungsmitteln über die Verzögerungsmittel ist.

5. Vorrichtung nach Anspruch 4, wobei die Verarbeitungsmittel so konfiguriert sind, dass sie die Phasensteuerungsmittel steuern, um die gemessene Leistung des Fehlersignals zu minimieren.

6. Vorrichtung nach einem der vorhergehenden Ansprüche, wobei eine aktuelle Verstärkung und Phase des verstärkten Signals von einer betrieblichen Historie des Leistungsverstärkers abhängig ist.

7. Satellit, umfassend:

einen Leistungsverstärker; und

die Vorrichtung nach einem der vorhergehenden Ansprüche, die so konfiguriert ist, dass sie die Verstärkung und Phase des Eingabesignals, das in den Leistungsverstärker eingegeben wird, steuert.

8. Verfahren zum Steuern einer Verstärkung und Phase eines Eingabesignals, das in einen Leistungsverstärker (301) eingegeben wird, wobei das Verfahren Folgendes umfasst:

Steuern der Verstärkung des Eingabesignals basierend auf einem Leistungsniveau des Eingabesignals und einem Leistungsniveau eines verstärkten Signals, das von dem Leistungsverstärker ausgegeben wird, um eine vorbestimmte Verstärkung des verstärkten Signals zu erlangen;

Verzögern eines aus dem Eingabesignal abgeleiteten ersten Signals;

Erlangen eines Fehlersignals, das mit einer Phasendifferenz zwischen dem verzögerten ersten Signal und einem zweiten Signal, das von dem verstärkten Signal abgeleitet wird, in Beziehung steht; und

Steuern der Phase des Eingangssignals gemäß dem Fehlersignal, um eine vorbestimmte Phase des verstärkten Signals zu erlangen, wobei das erste Signal derart verzögert ist, dass das verzögerte erste Signal und das zweite Signal, die zum Erlangen des Fehlersignals verwendet werden, demselben Teil des Eingangssignals entsprechen, wobei das Steuern der Verstärkung des Eingangssignals Folgendes umfasst:

Verwenden eines ersten Detektors (311), um ein Leistungsniveau des dritten Signals zu messen, das von dem Eingangssignal abgeleitet ist, und Verwenden eines zweiten Detektors (312), um ein Leistungsniveau eines vierten Signals zu messen, das von dem verstärkten Signal abgeleitet ist;

Vergleichen des Leistungsniveaus des dritten Signals und des Leistungsniveaus des vierten Signals; und

Steuern der Verstärkung des Eingangssignals basierend auf dem Ergebnis des Vergleichs,

dadurch gekennzeichnet, dass das Steuern der Verstärkung des Eingangssignals ferner Folgendes umfasst:

Skalieren einer Ausgabe des ersten Detektors oder einer Ausgabe des zweiten Detektors, sodass die Ausgaben des ersten und zweiten Detektors im Wesentlichen identisch sind, wenn das dritte und vierte Signal die gleiche Leistung haben.

Revendications

- Appareil de contrôle d'un gain et d'une phase d'un signal d'entrée entré dans un amplificateur de puissance (301), l'appareil comprenant :
 - un moyen de contrôle de gain (302) pour contrôler le gain du signal d'entrée ;
 - un moyen de contrôle de phase (303) pour contrôler la phase du signal d'entrée ;
 - une boucle de contrôle de gain (310) configurée pour contrôler le moyen de contrôle de gain sur la base d'un niveau de puissance du signal d'entrée et d'un niveau de puissance d'un signal amplifié émis par l'amplificateur de puissance, pour obtenir un gain prédéterminé du signal amplifié ; et
 - une boucle de contrôle de phase (320) configurée pour obtenir un signal d'erreur lié à une différence de phase entre un premier signal dérivé du signal d'entrée et un deuxième signal dérivé du signal amplifié, et contrôler le moyen

de contrôle de phase sur la base du signal d'erreur pour obtenir une phase prédéterminée du signal amplifié,

dans lequel la boucle de contrôle de phase est agencée pour retarder le premier signal avant d'obtenir le signal d'erreur, de sorte que le premier signal retardé et le deuxième signal utilisé pour obtenir le signal d'erreur correspondent à la même partie du signal d'entrée,

dans lequel la boucle de contrôle de gain est configurée pour recevoir un troisième signal dérivé du signal d'entrée et un quatrième signal dérivé du signal amplifié,

dans lequel la boucle de contrôle de gain est configurée pour comparer un niveau de puissance du troisième signal et un niveau de puissance du quatrième signal et contrôler le moyen de contrôle de gain sur la base du résultat de la comparaison, et

dans lequel la boucle de contrôle de gain comprend :

un premier détecteur (311) configuré pour mesurer un niveau de puissance du troisième signal ;

un second détecteur (312) configuré pour mesurer un niveau de puissance du quatrième signal ;

caractérisé en ce que la boucle de contrôle de gain comprend un moyen (315) pour mettre à l'échelle une sortie du premier détecteur ou une sortie du second détecteur, de sorte que les sorties des premier et second détecteurs sont sensiblement identiques lorsque les troisième et quatrième signaux ont la même puissance.

- Appareil selon la revendication 1, comprenant également :
 - un coupleur d'entrée (304) configuré pour recevoir le signal d'entrée et émettre le troisième signal, le coupleur d'entrée ayant un premier facteur de couplage ; et
 - un coupleur de sortie (305) configuré pour recevoir le signal amplifié et émettre le quatrième signal, le coupleur de sortie ayant un second facteur de couplage,

dans lequel les premier et second facteurs de couplage sont sélectionnés de sorte que lorsque le signal amplifié a le gain prédéterminé, le troisième signal et le quatrième signal ont sensiblement le même niveau de puissance.
- Appareil selon la revendication 1 ou 2, dans lequel le signal amplifié est écrêté par l'amplificateur de puissance, l'appareil comprenant également :
 - un limiteur configuré pour écrêter le signal d'entrée

en correspondance avec l'écrêtage du signal amplifié par l'amplificateur de puissance, de sorte que le troisième signal reçu par le premier détecteur et le quatrième signal reçu par le second détecteur sont écrêtés sensiblement de la même quantité.

4. Appareil selon l'une quelconque des revendications précédentes, dans lequel la boucle de contrôle de phase comprend :

un moyen de retardement (321) pour retarder le premier signal ;

un moyen de génération de signal d'erreur (322) pour générer le signal d'erreur sur la base du deuxième signal et du premier signal ;

un détecteur (323) pour mesurer une puissance du signal d'erreur ; et

un moyen de traitement (324) configuré pour contrôler le moyen de contrôle de phase sur la base de la puissance mesurée du signal d'erreur,

dans lequel le moyen de retardement est configuré de sorte que la longueur électrique d'un premier chemin vers le moyen de génération de signal d'erreur via l'amplificateur de puissance est sensiblement la même que la longueur électrique d'un second chemin vers le moyen de génération de signal d'erreur via le moyen de retardement.

5. Appareil selon la revendication 4, dans lequel le moyen de traitement est configuré pour contrôler le moyen de contrôle de phase afin de minimiser la puissance mesurée du signal d'erreur.

6. Appareil selon l'une quelconque des revendications précédentes, dans lequel un gain de courant et une phase du signal amplifié dépendent d'un historique opérationnel de l'amplificateur de puissance.

7. Satellite comprenant :

un amplificateur de puissance ; et

l'appareil selon l'une quelconque des revendications précédentes, configuré pour contrôler le gain et la phase du signal d'entrée entré dans l'amplificateur de puissance.

8. Procédé de contrôle d'un gain et d'une phase d'un signal d'entrée entré dans un amplificateur de puissance (301), le procédé comprenant :

le contrôle du gain du signal d'entrée sur la base d'un niveau de puissance du signal d'entrée et d'un niveau de puissance d'un signal amplifié émis par l'amplificateur de puissance, pour obtenir un gain prédéterminé du signal amplifié ;
le retardement d'un premier signal dérivé du

signal d'entrée ;

l'obtention d'un signal d'erreur lié à une différence de phase entre le premier signal retardé et un deuxième signal dérivé du signal amplifié ; et le contrôle de la phase du signal d'entrée sur la base du signal d'erreur pour obtenir une phase prédéterminée du signal amplifié, dans lequel le premier signal est retardé de sorte que le premier signal retardé et le deuxième signal utilisé pour obtenir le signal d'erreur correspondent à la même partie du signal d'entrée, dans lequel le contrôle du gain du signal d'entrée comprend :

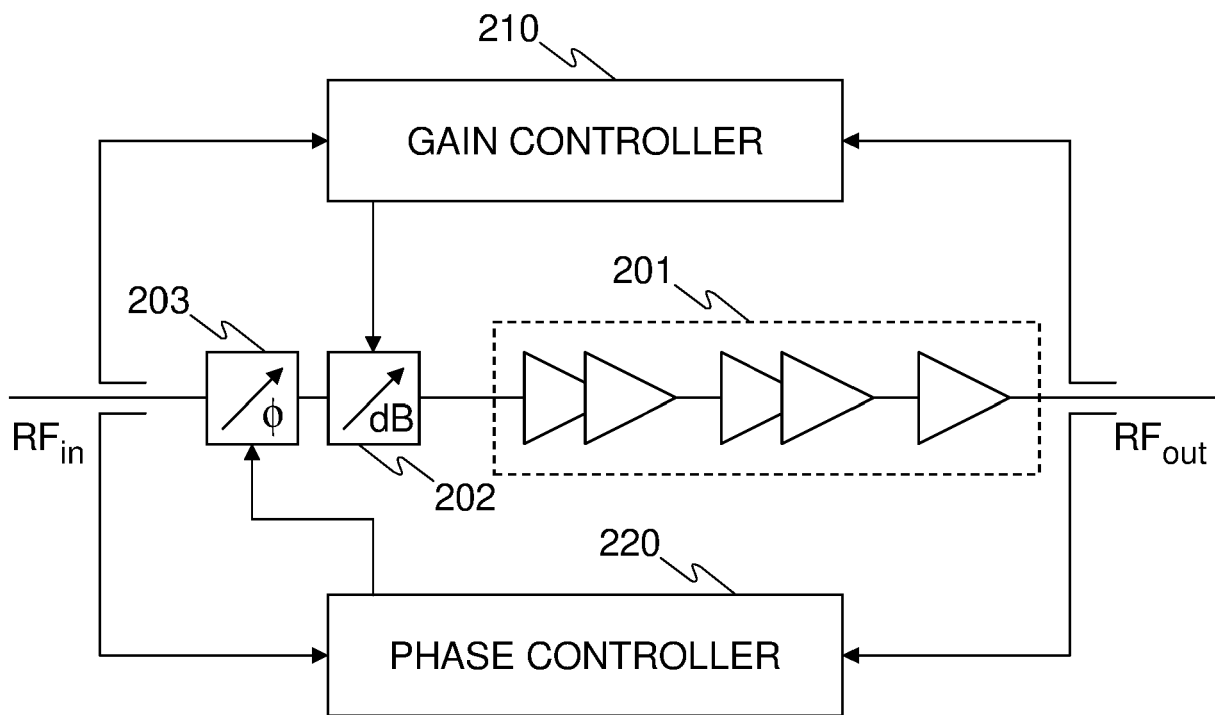
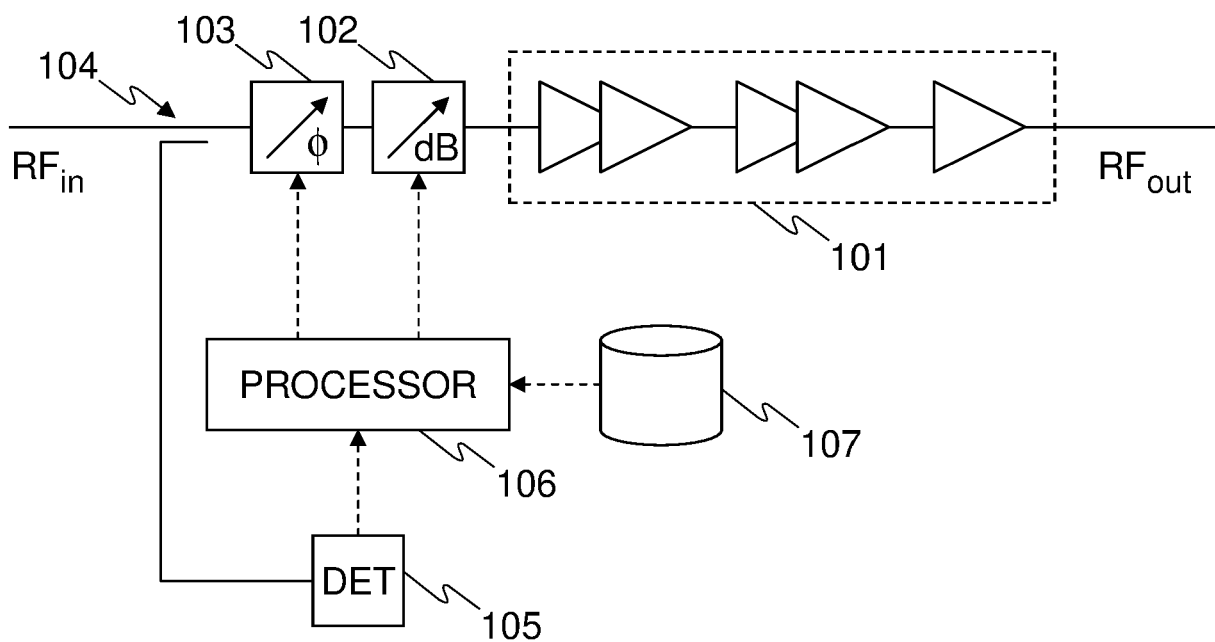
l'utilisation d'un premier détecteur (311) pour mesurer un niveau de puissance du troisième signal dérivé du signal d'entrée, et l'utilisation d'un second détecteur (312) pour mesurer un niveau de puissance d'un quatrième signal dérivé du signal amplifié ;

la comparaison du niveau de puissance du troisième signal et du niveau de puissance du quatrième signal ; et

le contrôle du gain du signal d'entrée sur la base du résultat de la comparaison,

caractérisé en ce que le contrôle du gain du signal d'entrée comprend également :

la mise à l'échelle d'une sortie du premier détecteur ou d'une sortie du second détecteur, de sorte que les sorties des premier et second détecteurs sont sensiblement identiques lorsque les troisième et quatrième signaux ont la même puissance.



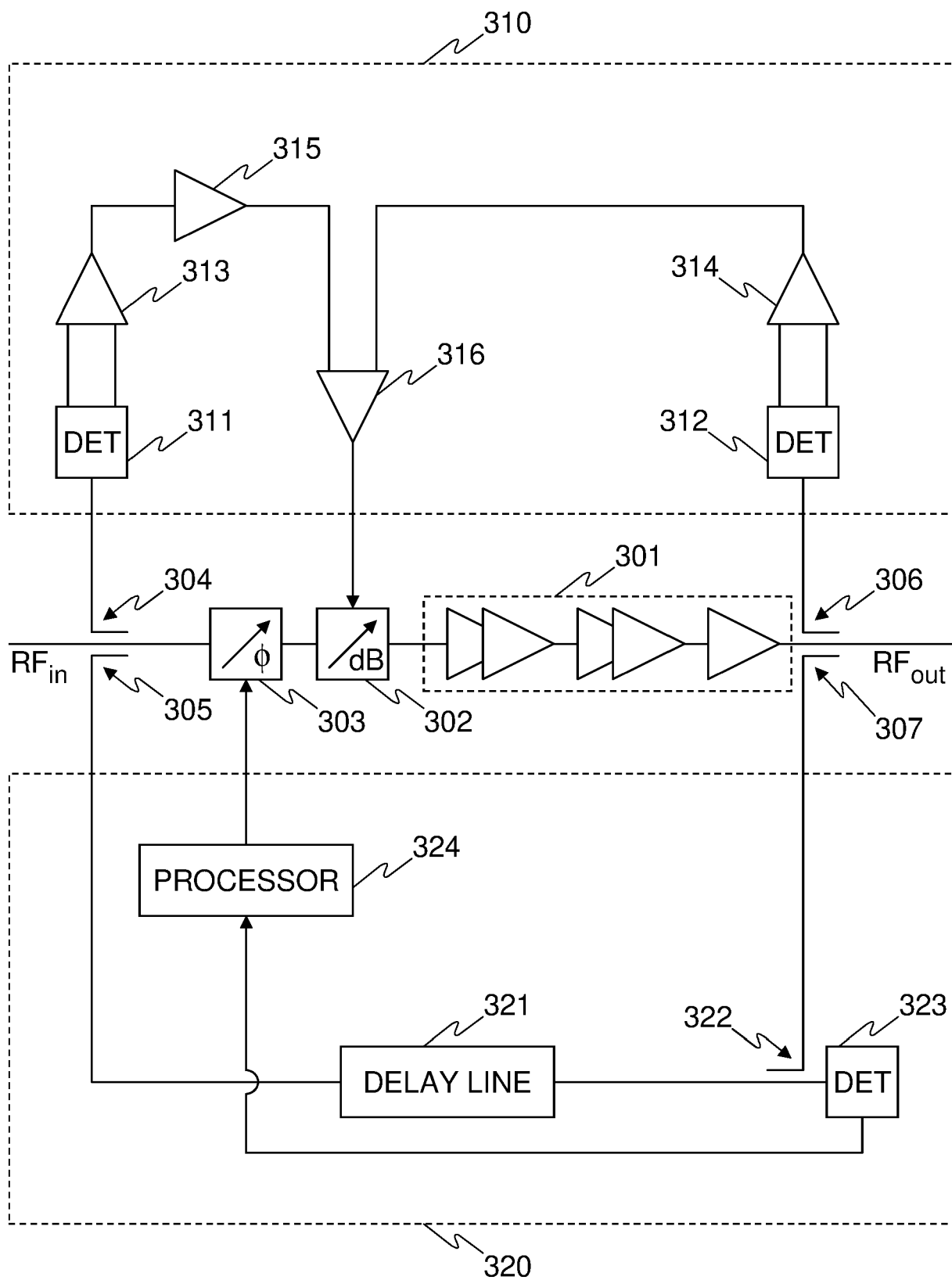


FIG. 3

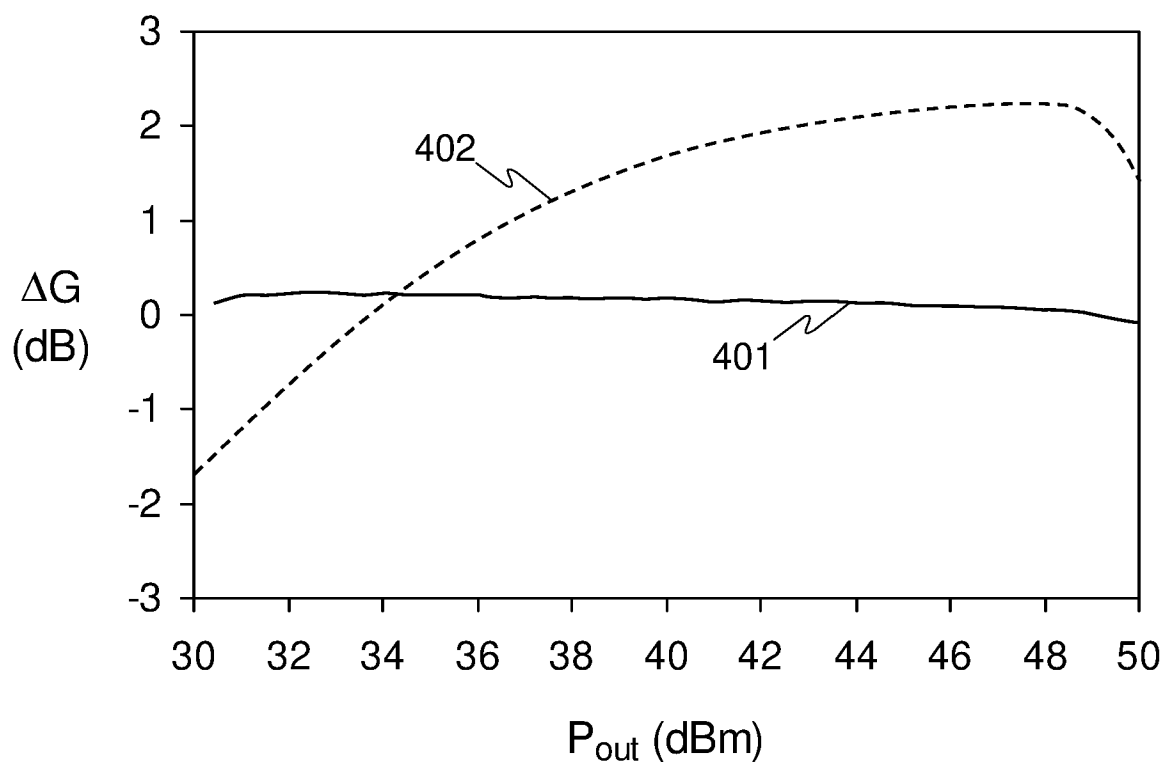


FIG. 4

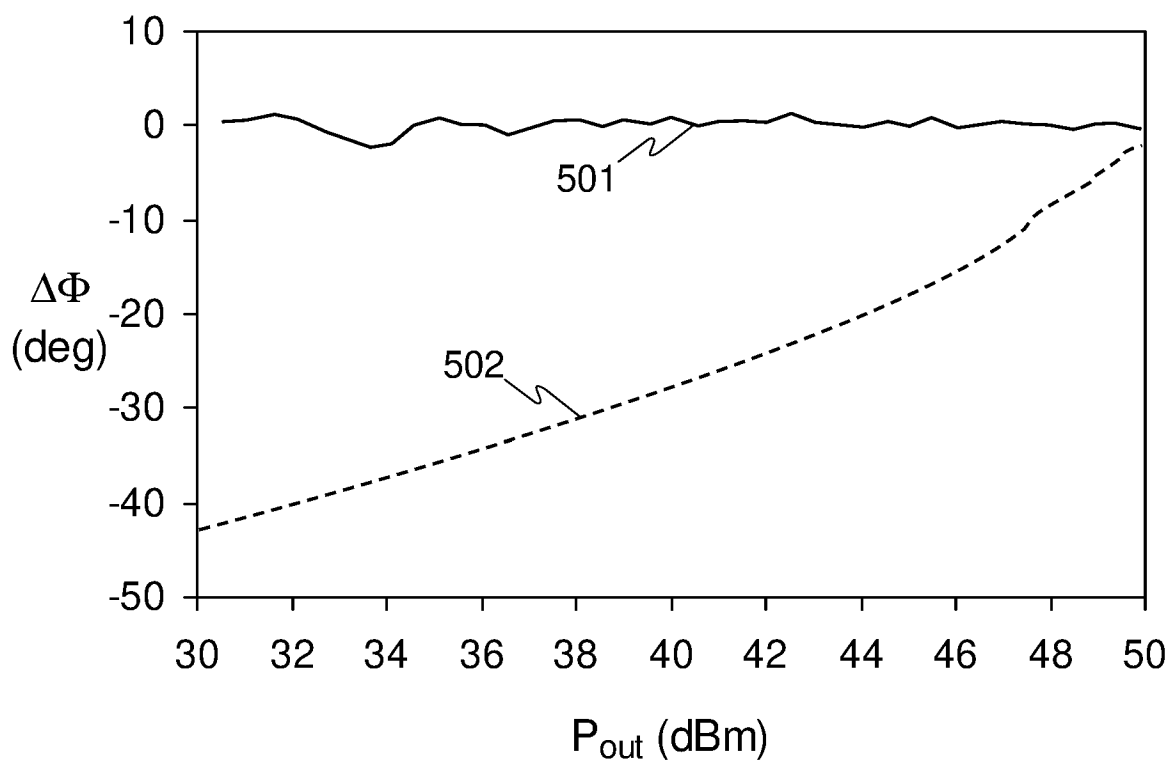


FIG. 5

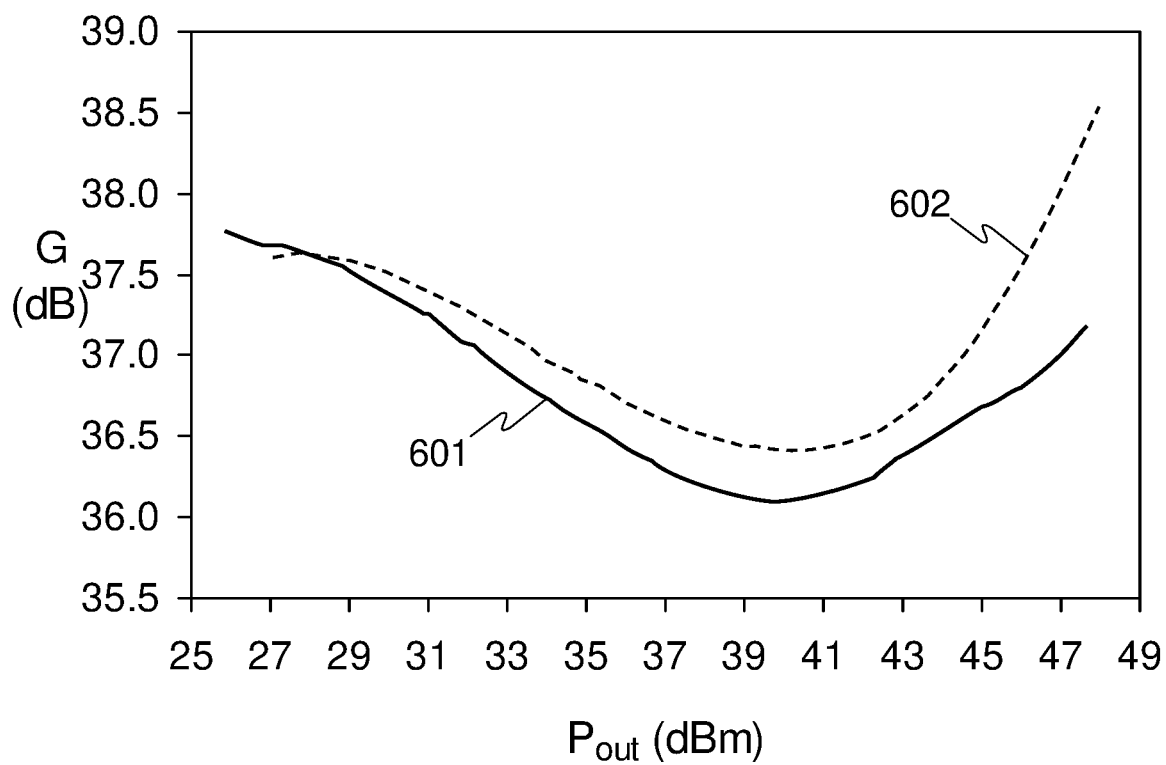


FIG. 6

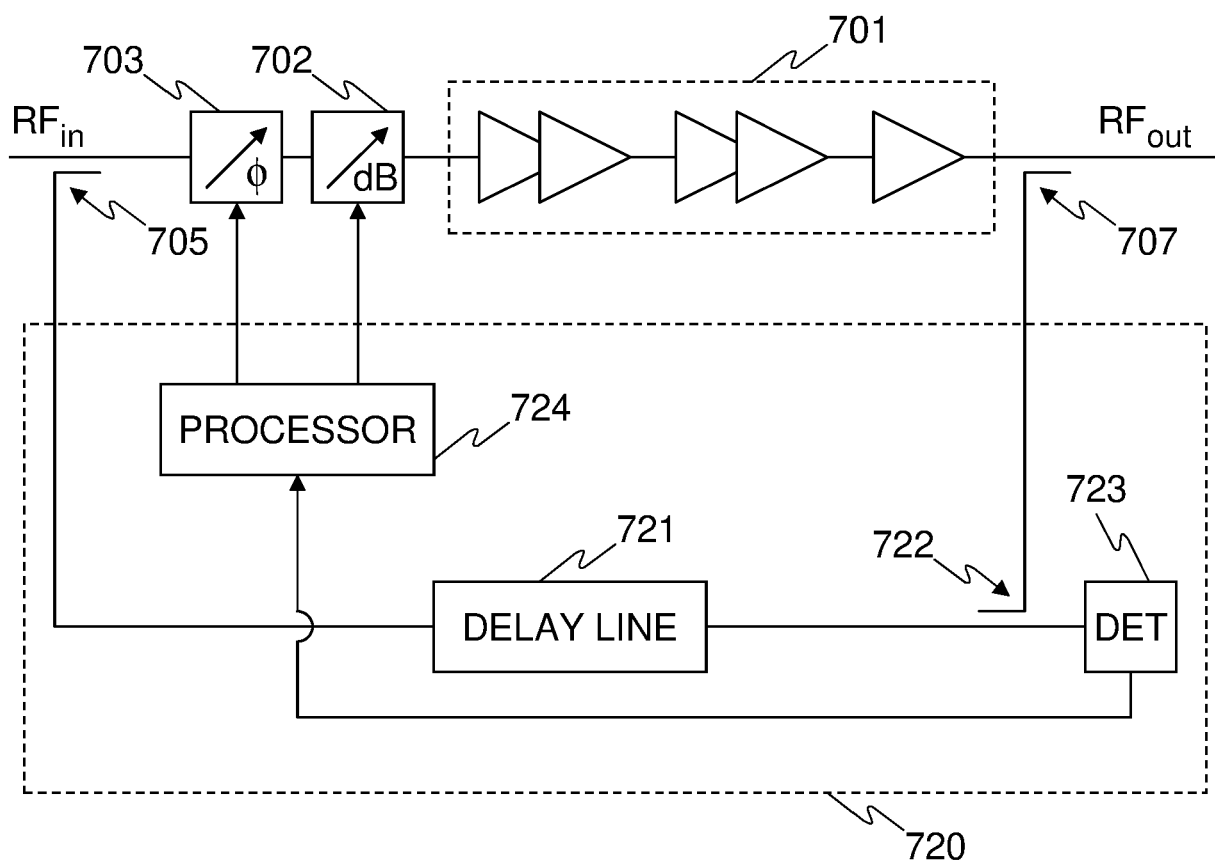


FIG. 7

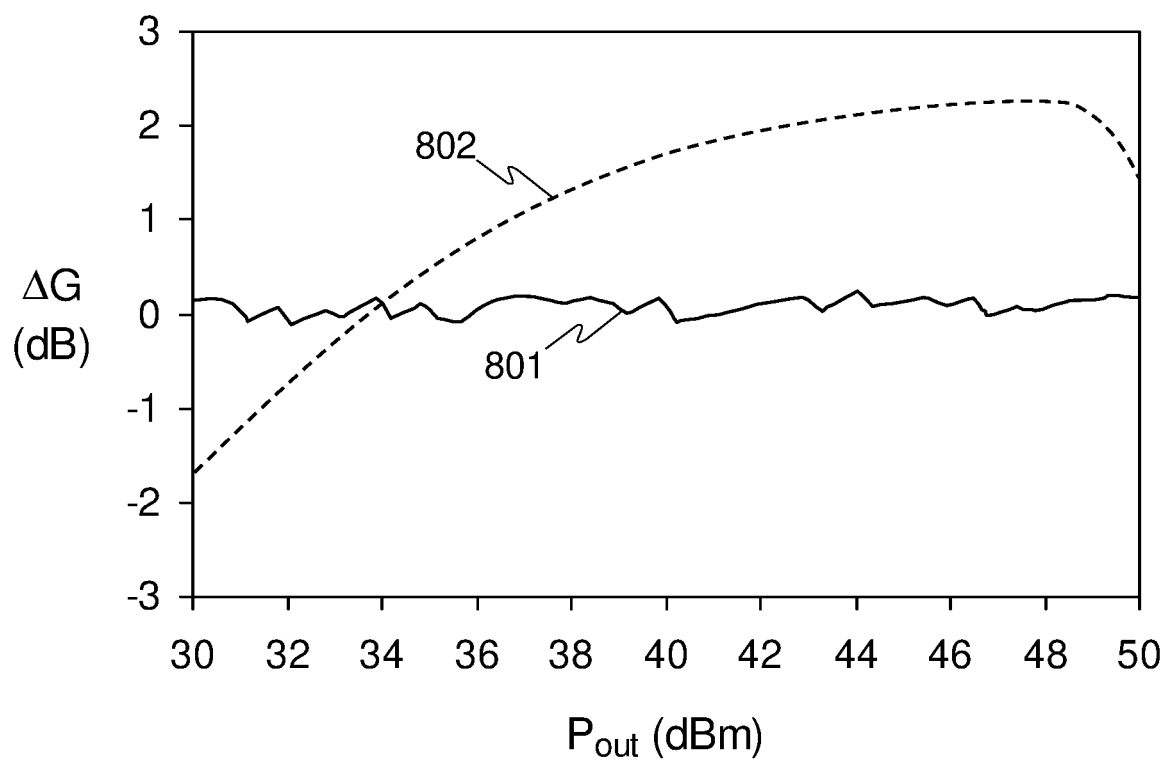


FIG. 8

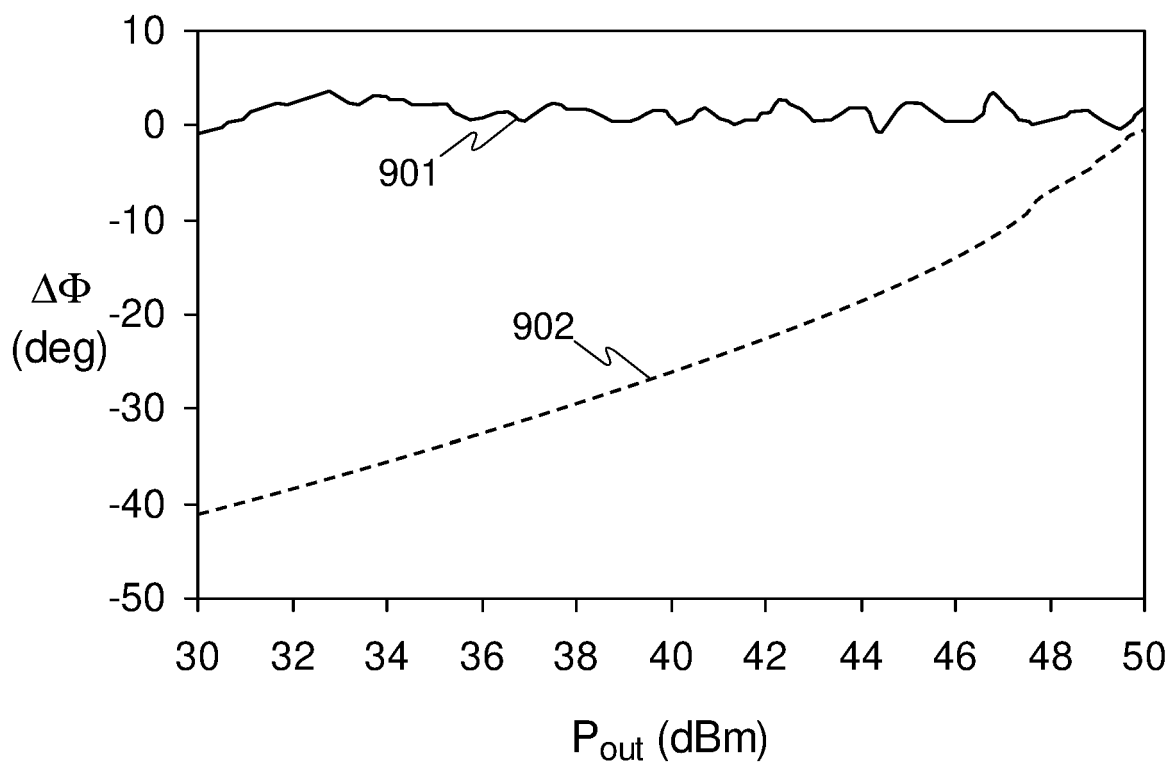


FIG. 9

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- US 2007184794 A1 [0006]
- US 6385436 B1 [0006]
- WO 0016473 A1 [0006]
- WO 9728598 A1 [0006]
- US 3900823 A [0006]